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Tropical Cyclone Forecasters Reference Guide
6. Tropical Cyclone Intensity

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One of the keys to safe and successful naval operations in the tropics is an understanding of tropical meteorology. The Tropical Cyclone Forecasters Reference Guide is designed primarily as a ready reference for weather forecasters required to provide tropical meteorology support to staff commanders. This report provides an overview of tropical cyclone intensity forecast support and is Chapter 6 of the reference guide. Subjects discussed include tropical cyclone intensity forecast procedures, major warning center operations, and tropical cyclone intensity terminology.

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TROPICAL CYCLONE FORECASTERS REFERENCE GUIDE

6. TROPICAL CYCLONE INTENSITY

1. INTRODUCTION

Tropical cyclone (TC) intensity is a measure of the strength of winds associated with a tropical cyclone. Intensity can be defined as the near-surface sustained wind speed or as minimum surface pressure at the TC center.

1.1 Intensity Forecasting vs. Motion Forecasting

Forecasts of tropical cyclone intensity are considerably more difficult than forecasts of tropical cyclone motion. In the relative sense, atmospheric processes responsible for the major portion of tropical cyclone motion are rather obvious, not overly complex and of a large scale. In contrast, those governing tropical cyclone intensity changes are not so obvious, very complex and are of multiple scales. Confounding the issue is that the initial intensity and intensity trend are often not known with a sufficient degree of precision.

1.2 Lack of Objective Guidance

As a consequence, intensity forecasts are highly subjective and not very skillful when compared to forecasts based on simple climatology and persistence. Numerical and statistical models have had reasonable success with motion forecasts, but not with intensity forecasts. Indeed, up until very recently, those working with models dealing with intensity changes have been discouraged with their inability to improve over forecasts based on climatology and persistence. For example, Merrill (1987), attempting to use synoptic predictors in a statistical intensity prediction model concludes, "These results...would seem to indicate that prediction of intensity change using classical statistical treatment of basic climatology and persistence and existing synoptic data or analyses has reached a dead end..."

More recently, some limited success in the prediction of tropical cyclone intensity change by both statistical and numerical models has been achieved. However, for the most part, skill in the prediction of motion is much greater that that of predicting intensity. As will be shown, intensity prediction errors can be rather high.

1.3 Impact of Incorrect Intensity Forecasts

Operational forecasters should recall that one of the most significant decisions required by operational commanders is whether or not to sortie ships that are threatened by tropical cyclones.

If the threat turns out to be a false alarm, a decision to evacuate is very expensive. On the other hand, a decision not to evacuate, should the threat materialize, could be even more expensive.

Tropical cyclone motion and intensity forecasts and associated errors are closely related. From an operational commander's point of-view, a reasonably correct forecast of tropical cyclone motion could be completely offset by an incorrect intensity forecast or vice versa. In addition to these meteorological factors, much depends on the type of ship, the degree of readiness, the protection afforded by the port, etc. Thus, the question of whether or not to evacuate is a complex issue and is based both on meteorological and non-meteorological factors.

2. **OBSERVATION AND FORECAST ERRORS**

In addition to the errors inherent in the forecast process itself, errors in the prediction of TC intensity can arise from uncertainties about the current storm maximum wind speed and the radial wind distributions in the various storm quadrants. This deficiency is also related to wind averaging times (sustained winds vs. gusts). These factors are discussed in this section.

2.1 Measurement of Tropical Cyclone Winds

Forecasters should be aware that the maximum wind speeds in tropical cyclones, as well as the radial decrease of wind from the radius of maximum wind speed, are seldom measured with a degree of precision implied by wind definitions. Tropical cyclones rarely pass directly over measurement devices. When they do, the devices are often incapacitated by the strong wind speed. Thus, there is heavy reliance on indirect estimates of surface tropical cyclone wind speeds and directions such as wind data provided by aircraft, satellite cloud imagery, radar, etc. However, Gray, et al. (1991) have shown that intensity estimates from these platforms are subject to various degrees of error.

Forecasters will note that intensity estimates are often stated in terms of pressure rather than wind speed. There is a strong empirical and theoretical relationship between these two parameters, thus they are used interchangeably to describe intensity. In the western North Pacific, the Atkinson-Holliday (1977) statistical relationship between wind and pressure is used by Navy personnel. Some solutions to their wind/pressure regression equation are given in Table 6.1.

Table 6.1. Average central pressure (mb) to average maximum intensity (kt) conversion table for western North Pacific tropical cyclones (after Atkinson and Holliday, 1977). Individual tropical cyclones may deviate from these averages.

Pressure (mb)	Wind Speed (kt)		Pressure (mb)	Wind Speed (kt)
1005	22		940	103
1000	30		935	108
995	38		930	113
990	46		925	117
985	53		920	122
980	60		915	126
975	66		910	130
970	72		905	134
965	78		900	138
960	83		895	142
955	88		890	146
950	94		885	150
945	99		880	154

Martin (1988) found that the most accurate intensity estimates (other than those from a ship or land site actually within a storm) are provided by reconnaissance aircraft observations. These types of observations are only available in the Atlantic and central Pacific. The mean absolute intensity observation error by aircraft is approximately 5 mb. The mean error is approximately 15 mb when the primary fix platform is satellite and 12 mb when the primary fix platform is radar.

Using satellite imagery for intensity estimates can sometimes cause a serious underestimation of storm intensity at the critical decision levels (50 to 70 kt). For example, a satellite intensity estimate is reported to be 40 kt, which, as shown in Table 6.1, is equivalent to 995 mb central pressure. Subtract the mean error associated with satellite estimates (15 mb) and the central pressure becomes 980 mb which is equivalent to 60 kt. Decisions made based on a 60-kt forecast are much different than for those based on a 40-kt forecast. Therefore, great caution should be used when making recommendations based on satellite fixes alone. Satellite fixes are used extensively in the Pacific and Indian oceans.

2.2 Wind Speed Averaging Times

Since surface winds and gusts can change dramatically over short time intervals, it is necessary to define the length of time over which the winds are to be measured. For a cyclone of some given intensity, longer wind averaging times will yield lower maximum winds. Unfortunately, different meteorological services use different averaging times. Following World Meteorological Organization (WMO) guidelines, most regions use a 10-minute average. However, the Joint Typhoon Warning Center (JTWC), Guam, and WMO Region IV (United States and Caribbean area) use a 1-minute standard average. A tropical cyclone defined as a typhoon using a 1-minute standard may not be defined as a typhoon using a 10-minute standard. Winds averaged over periods of at least 1 minute are referred to as <u>sustained</u> winds.

By examining a large number of recorded wind speeds vs. time traces and damage reports, conversion factors for going from one averaging time to another have been derived (Fujita, 1971; Simiu and Scanlon, 1978; Krayer and Marshall, 1982). Depending on the methodology, there are some small differences in recommended conversion factors. For US Navy interests, the factor 0.88 is used in going from a 1-minute system to a 10-minute system such that TEN-MINUTE MEAN = 0.88 * ONE-MINUTE MEAN or ONE-MINUTE MEAN = 1.14 * TEN-MINUTE MEAN. Appendix A provides two tables for converting between 1-minute wind speeds and 10-minute wind speeds. These conversion factors should be considered as average rather than absolute conversions. There are many variations depending mainly

on the frictional characteristics of the surface area and the atmospheric stability.

2.3 Gusts

Sudden brief increases and decreases in the wind speeds are called gusts and lulls, respectively (Huschke, 1959). Gusts or lulls can be much higher or lower than the sustained wind speed. Since gusts can substantially increase the damage potential from a tropical cyclone, expected gusts are included in tropical cyclone warnings. Conversion factors have been derived between sustained wind and gusts. The U.S. standard used at JTWC is given in table 6.2.

Table 6.2. Gusts expected with one-minute mean sustained surface wind speeds.

ONE MINUTE MEAN WIND (kt)	GUSTS (kt)
30	40
35	45
40	50
45	55
50	65
55	70
60	75
65	80
70	85
75	90
80	100
85	105
90	110
95	115
100	125
105	130
110	135
115	140
120	145
125	150
130	160
135	165

2.4 Intensity Forecast Errors

As discussed earlier, the physical processes associated with TC intensity are complex and not well understood. Operational statistical and numerical weather prediction models have some difficulty in improving over forecasts based on simple climatology and persistence models. Forecasts based on simple statistical models do not adequately address the occasional rapid deepening and filling of tropical cyclones. Thus, forecast errors of TC intensity are rather high.

Table 6.3, with data taken from the annual JTWC Typhoon Report, summarizes the JTWC maximum wind speed forecast errors for a recent 5-year period for the western North Pacific. The bias is simply the algebraic average of the forecast maximum wind speed errors, in the sense of forecast minus observed. Thus, positive bias indicates that the forecast more often called for maximum wind speeds higher than observed while negative bias indicates that the maximum wind speed forecast was not high enough. The average errors (Table 6.3) are positive and increase with forecast period. Average wind forecast error is considered a poor error estimation since the positive and negative errors compensate each other.

Average absolute error gives a better indication of error. These errors (Table 6.3) are 11.2, 17.9 and 24.5 kt for 24-, 48- and 72-hour forecasts, respectively. Note that, for the 72-hr forecast, absolute wind forecast errors of at least 25 kt are seen to occur about 47% of the time. Most (27.8%) of these 72-hr errors of at least 25 kt are associated with the maximum wind being forecast too high (27.8%).

Additional details of the 72-hr error pattern are provided in Figures 6.1a and 6.1b. The former presents a frequency distribution of specific error values. Here, the small bias towards positive values (maximum wind forecast error too high) is quite apparent. Data from Figure 6.1a were used to prepare the cumulative percentage frequency (CPF) plot shown in Figure 6.1b. Here, the errors are presented without regard to whether the forecast winds were too high or too low.

Some of the very high wind forecast errors depicted in Figures 6.1a and 6.1b are often related to motion forecast errors. Intensifying tropical cyclones, if expected to remain over a favorable marine environment, would logically be expected to continue deepening. However, an incorrect motion forecast with the storm moving over a land area, rather than remaining at sea, could result in large intensity forecast errors. This event often occurs in connection with tropical cyclones moving northwestward off the east coast of Luzon where the intensity is heavily dependent on whether the storm passes over Luzon or remains at sea.

While the intensity errors noted in Table 6.3 and in Figs. 6.1a and b may appear to be rather high, intensity forecasts for other basins show similar error patterns. At the National Hurricane Center (NHC), for example, long term North Atlantic absolute wind speed forecast errors have averaged 11.5, 16.4 and 20.7 knots at 24-, 48- and 72-hours, respectively. The slightly lower Atlantic error at 72h is due to the fact that Atlantic systems typically do not reach the severity of the western Pacific tropical cyclones.

Table 6.3. Joint Typhoon Warning Center (JTWC) maximum wind speed forecast errors (forecast minus observed) for the western North Pacific basin for 5 years (1988, 1989 and 1991 through 1993). Positive and negative signs indicate intensity forecast errors are too high and low, respectively.

Parameter	24-hr fcst	48-hr fcst	72-hr fcst
avg error (bias)	+0.1 kt	+1.5 kt	+3.9 kt
avg absolute error	11.2 kt	19.9 kt	24.5 kt
max pos error (fcst high)	+85 kt	+85 kt	+95 kt
max neg error (fcst low)	-60 kt	-80 kt	-85 kt
errors at least 25kt high	5.8 %	16.0 %	27.8 %
errors at least 25kt low	7.2 %	14.3 %	19.4 %
errors at least 25kt high or low	13.0 %	30.3 %	47.2 %
sample size	3249	2588	1922

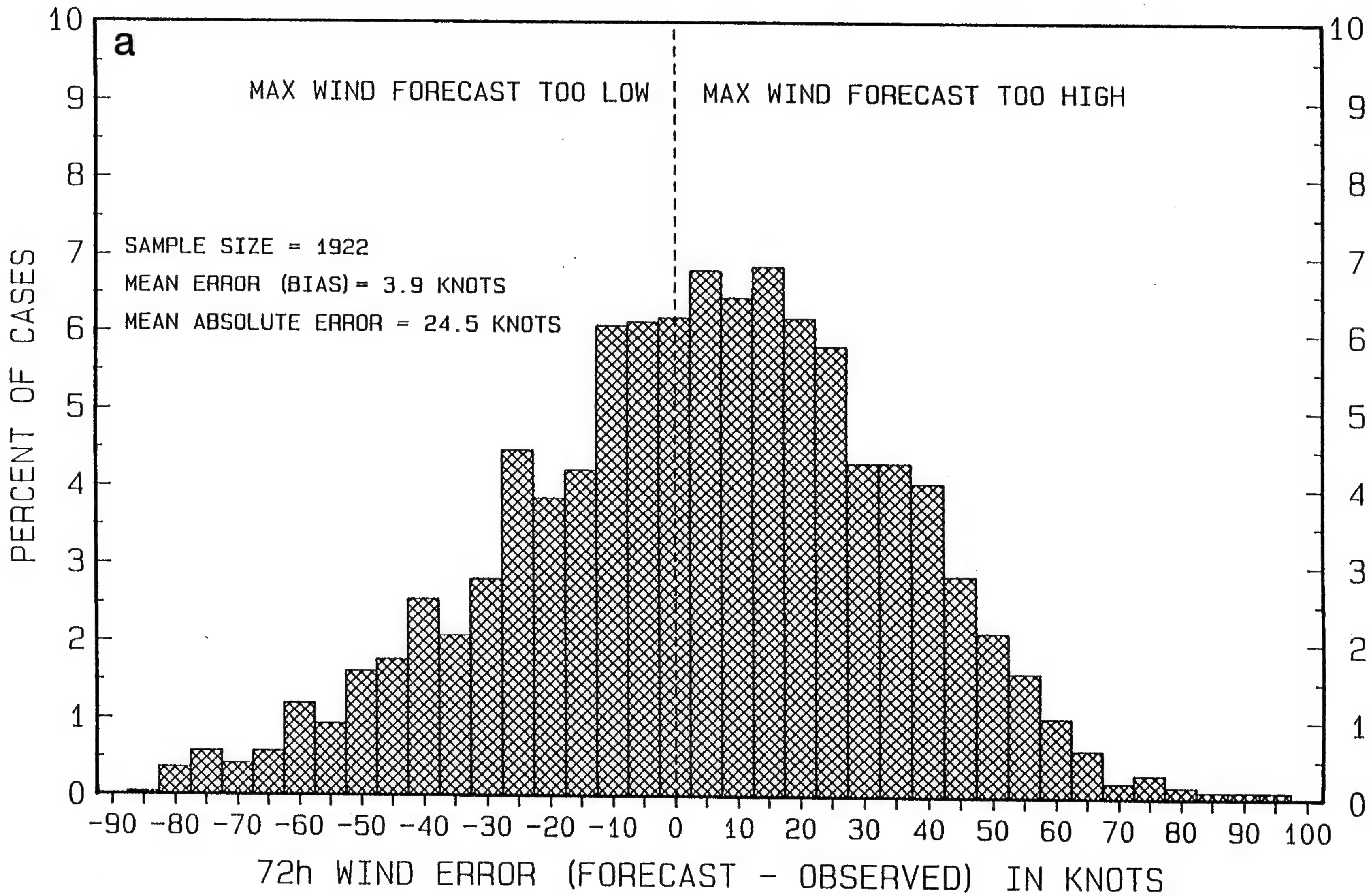

Fig. 6.1 JTWC 72h maximum wind forecast error (knots) over 5-year period 1988, 1989, 1991, 1992 and 1993. (a) Frequency distribution of errors by 5-knot class intervals where positive/negative forecast errors indicate that forecast was too high/low. (b) cumulative percentage frequency distribution of errors in (a) but without regard to whether error was too high or too low.

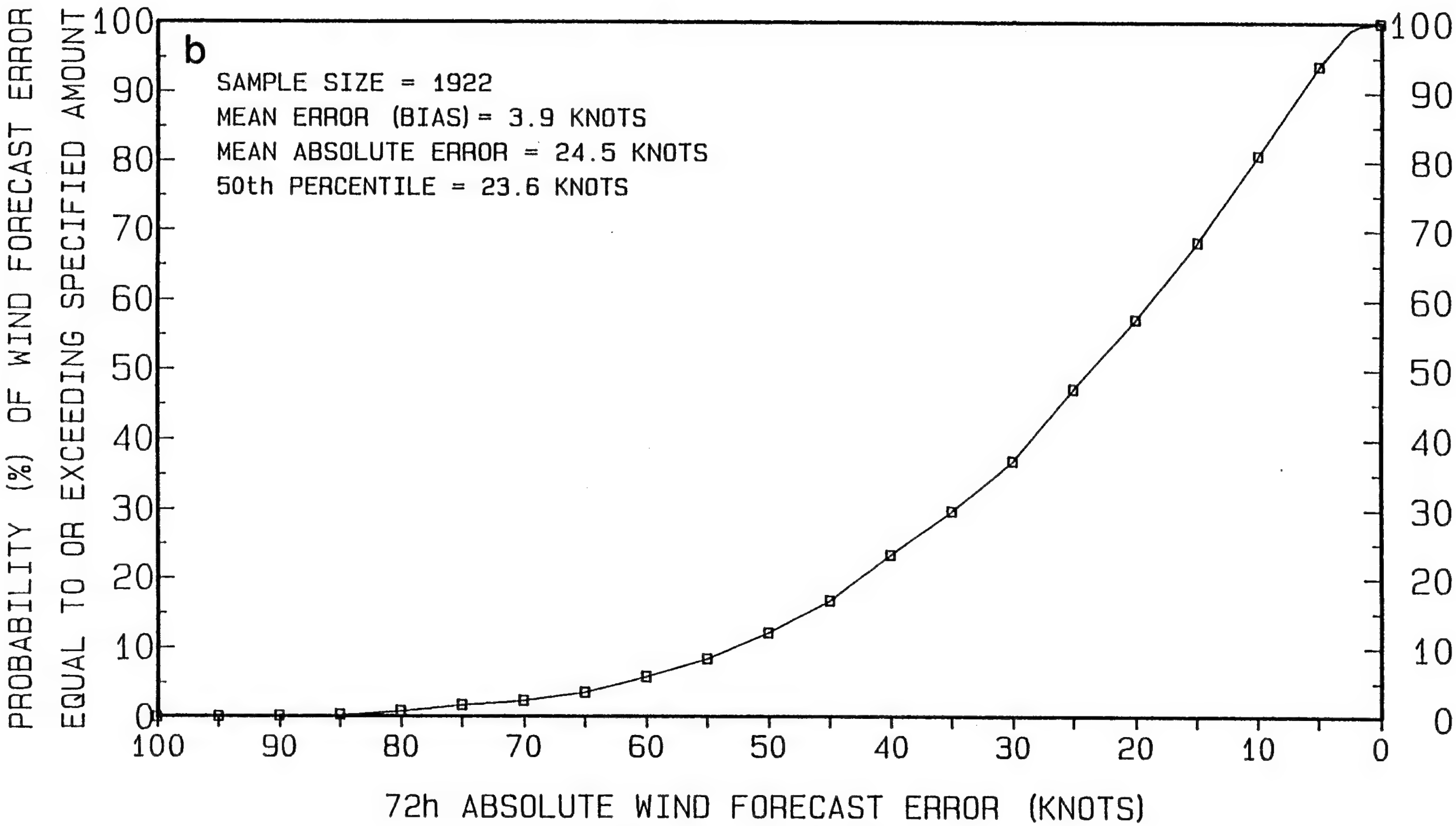

Fig. 6.1, continued.

3. TROPICAL CYCLONE INTENSITY TERMINOLOGY

Although the World Meteorological Organization provides general TC intensity terminology (Huschke, 1959), individual forecast agencies may have their own terminology. This section describes terminology used by the U.S. Department of Defense (DOD) and the U.S. Department of Commerce (DOC).

3.1 US DOD Intensity Classification

The DOD classification for tropical cyclones is based on the one-minute average mean wind speed. Most other forecast agencies around the world use a ten-minute average mean. This difference in intensity results in confusion between intensity forecasts among the warning agencies. Table A-1 shows a comparison of the one-minute and ten-minute mean winds for a given sea level pressure. The following are the five intensity classes used by DOD.

1. Tropical Disturbance. A discrete system of loosely organized convection generally 100 to 300 nm in diameter, originating in the tropics or subtropics, having a non-frontal, migratory character and having maintained its identity for 12 to 24 hours. It may or may not be associated with a detectable wave perturbation of the low-level wind or pressure field.

2. Tropical Depression. A TC that may have one or more closed isobars and maximum 1-minute mean sustained surface wind speeds of 33 kt or less.

3. Tropical Storm. A TC with maximum 1-minute mean sustained surface wind speeds in the range of 34 to 63 kt inclusive.

4. Typhoon or Hurricane. A TC with maximum sustained 1-minute mean surface wind speeds of at least 64 kt. West of 180 degrees longitude they are called typhoons and east of 180 degrees longitude they are called hurricanes.

5. Super-Typhoon. A typhoon with maximum sustained 1-minute mean surface wind speeds of 130 kt or greater.

3.2 US DOC Intensity Classification

The DOC/NOAA/NHC uses the same intensity classification as DOD does except that there is no super-hurricane class. In addition, the NHC has adopted the Saffir-Simpson Hurricane Scale for Atlantic hurricane intensity (Table 6.4). This scale consists of five categories (weak, moderate, strong, very strong and devastating) indicating damage due to high winds and storm surge. The primary purpose of this scale is to provide hurricane forecasters with the

vocabulary to communicate estimates of damage potential to their customers.

The Saffir-Simpson Hurricane Scale is an application of the Fujita Tornado Scale or F-scale (Fujita, 1971, NHOP, 1994) which estimates tornado wind speeds from damage reports. As there are major statistical differences between Atlantic hurricanes, Pacific hurricanes, and Pacific typhoons, Table 6.4 should be used only for Atlantic hurricanes.

Table 6.4. The Saffir-Simpson Hurricane Scale for Atlantic hurricane intensity.

Saffir-Simpson Hurricane Scale	1-Min. Wind Speed in kt (mph)	Storm Surge in ft (m)
Category One -- weak	65 - 82 (75-95)	4 - 5 (1.2-1.5)
Category Two -- moderate	83 - 95 (96-110)	6 - 8 (1.8-2.4)
Category Three -- strong	96 - 113 (111-130)	9 - 12 (2.7-3.7)
Category Four -- very strong	114 - 135 (131-155)	13 - 18 (3.9-5.5)
Category Five -- devastating	greater than 135 (155)	greater than 18 (5.5)

3.3 **Intensity Trends**

Intensity trend is defined as the change of intensity with time. The terms "intensifying" and "deepening" refer to positive intensity trends while the terms "decaying" and "filling" are used for negative intensity trends.

Tropical cyclones that rapidly deepen (or rapidly intensify) and are not forecast to do so pose a serious threat to operational commanders. Although the concept of rapid deepening is clear, the definition, as shown in Table 6.5, is rather arbitrary. Globally, about 15% of all tropical cyclones experience a period of rapid intensification. When applied to an individual year in the western Pacific, rapid intensification has been as high as 37%. When applied to the South China Sea, this statistic is observed to be as low as 1%.

Tropical cyclones that dissipate over water exhibit a large range of dissipation rates. Storms that weaken slowly usually are affected by moderate vertical wind shear or are moving over slightly lower sea surface temperatures (SSTs). These storms can take three to five days to weaken. Tropical cyclones that decay rapidly over water are either affected by strong vertical wind shear or are moving over much lower SSTs. These storms take one to three days to dissipate. Tropical cyclones that move over land decay rapidly due to the loss of the warm moist maritime heat source. These storms typically dissipate in one to two days, although the strongest winds in the core can weaken significantly in less than one day.

The Dvorak technique (Dvorak, 1973) has been widely adopted for describing satellite-based TC intensity trends. This technique provides the experienced analyst with a procedure in which the interpretation of satellite imagery is combined with a model of TC development. The model describes cyclone development and dissipation as a day-to-day progression through recognizable combinations of cloud characteristics. See Appendix B for an expanded discussion of this technique.

Table 6.5. Tropical cyclone development trend classifications.

Classification Source	Short Term Trend	12-Hour Trend	24-Hour Trend
Holliday & Thompson (1979), Rapid Deepening	>1.75 mb/hr	none	> 42 mb/day
JTWC Rapid Deepening	= or > 1.25 mb/hr	none	= or > 30 mb/day
JTWC Explosive Deepening	5.0 mb in 6 hours	2.5 mb/hr for 12 hours	none
Dunnavan (1981), Rapid Deepening	5.0 mb in 6 hours	2.5 mb/hr for 12 hours	none
Brand (1973), Rapid Deepening	none	none	50 knot wind increase in 24 hrs.
Normal Development Trend	none	none	10 to 41 mb in 24 hr.

4. LIFE CYCLE OF TROPICAL CYCLONES

There are several schemes that describe the life-cycle of an average TC. The three schemes shown in Table 6.6 consist of three to four stages. These stages are not really discrete entities, rather they represent a continuous process. Individual stages may even occur more than once during the life-cycle of a particular storm.

4.1 Formation or Genesis Stage

Since the nature of TC development is continuous, features associated with earliest stages of the TC life-cycle can overlap. To complicate the issue, there is no standard language for these initial stages. For example, some meteorologists prefer the term "genesis" to describe both the earliest stages of the life-cycle and progression to a mature hurricane or typhoon. Others use the term "genesis" to describe the earliest stages and "formation" for somewhat later stages in the life-cycle.

4.2 Intensification or Deepening Stage

In this stage, the TC central pressure falls and the maximum surface wind speed increases. An eye may develop at the center of the TC if the stage continues.

4.3 Mature Stage

The mature stage of a TC is usually associated with the period in which the TC reaches maximum intensity. The central pressure has reached a minimum, and the surface winds have reached a maximum.

4.4 Decay Stage

When a TC decays, the central pressure increases and the maximum surface winds weaken. Usually, the decaying process is the result of a TC moving over land, moving over cool water, recurving and assuming extratropical characteristics, or a combination of these processes. Even though the TC is decaying, it can produce high winds and heavy rains.

Table 6.6. Tropical cyclone life-cycle schemes.

Stage of TC develop-ment	Dunn (1951), Riehl (1979)	Yanai (1964)		Anthes (1982)
1	Formative or incipient -- begins when a TD first develops surface circulation and ends when TC reaches hurricane intensity.	Formation --	Wave disturbances -- the potential embryo of TC genesis.	Genesis -- begins when cumulus cluster embedded in an unstable wave disturbance and ends when TC eye forms. In 24 hours toward the end of this stage, TC has intensified to a mature hurricane.
			Warming -- cold-core disturbance transforms into warm-core one.	
			Developing -- mean temperature of the upper troposphere increases, while surface pressure decreases.	
2	Immature or deepening -- TC continues to deepen until the lowest central pressure and the maximum intensity are reached.	Mature -- similar to Dunn (1951).		Mature -- hurricane reaches a nearly steady state while low-level inflow, organized deep convection, upper tropospheric outflow and tangential wind speeds are in dynamic and thermodynamic balance.
3	Mature -- TC stops deepening. Surface isobars are spreading out, but intensity appears steady or is decreasing.	Decay -- Similar to Dunn (1951).		Decay -- Similar to Dunn (1951).
4	Decay -- When the TC is dissipating over land or is recurving northward and assuming extratropical characteristics.	N/A		N/A

5. FACTORS AFFECTING INTENSITY

Many of the physical processes associated with tropical cyclone intensification and decay are difficult to observe and poorly understood. Nevertheless, it is possible to determine whether some of these physical processes encourage or discourage tropical cyclone intensification (Appendix C).

In regard to practical approaches to intensity prediction, forecasters are generally limited to analysis of synoptic patterns. A few of the observable synoptic patterns are discussed in this section.

5.1 Upper-level Anticyclones

As viewed by satellites, upper-troposphere patterns associated with intensification are the easiest to identify because lower levels are usually obscured by clouds. These upper-troposphere patterns can define the outflow at the top of the TC, which indicates mass removal from the center of the storm (Fig. 6.2).

In general, a mesoscale anticyclone is located directly over or near the center of the TC. This represents the location in the upper wind field where there is a buildup of mass from rising convective motion within the center of the cyclone.

On the other hand, another larger, synoptic scale anticyclone is often found that pre-existed within the vicinity of the intensifying TC. The location of this larger anticyclone can vary depending upon many environmental factors, including the lower-level forcing mechanisms that are helping to create the cyclone.

The relative location of this large-scale anticyclone with respect to the TC will help dictate the direction of outflow patterns around the cyclone. These outflow patterns can be classified into one of three basic categories depending on the number of channels: single-channel, double-channel, or no outflow channel. These outflow patterns can be identified from satellite infrared cloud imagery, especially when the imagery is animated.

5.1.1 **Single-channel Outflow**. The single-channel outflow may be divided into two subcategories based on direction of the outflow channel. Tropical cyclones with single-channel poleward outflow pattern (Fig. 6.3) generally intensify at an average maximum rate of 15 to 20 kt/6 hr. Tropical cyclones with single-channel equatorward outflow pattern (Fig. 6.4) generally intensify at an average maximum rate of 25 to 28 kt/6 hr.

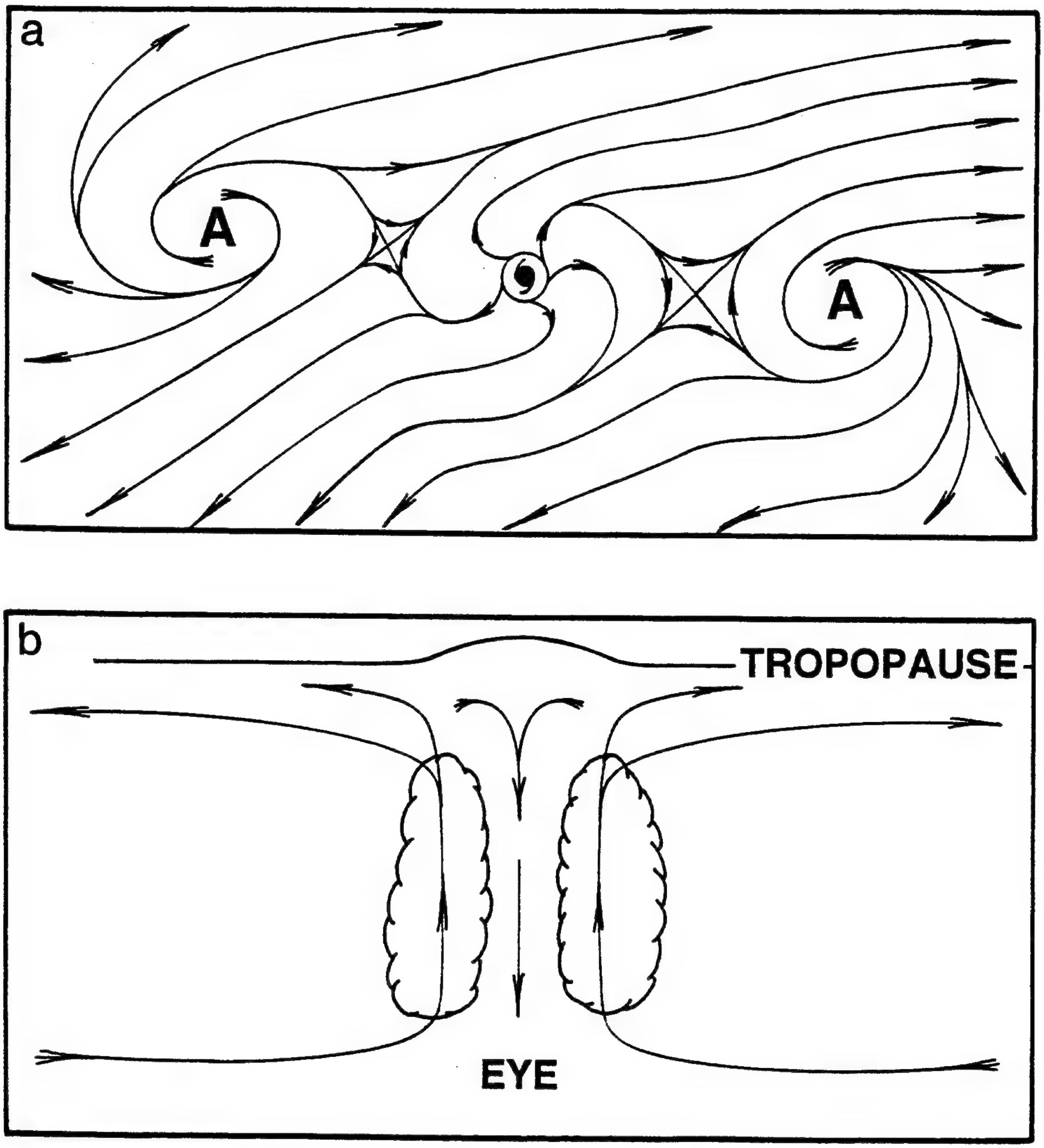

Fig. 6.2 Sketch of a typhoon's (a) upper-tropospheric streamlines and (b) vertical circulation. Note that the scales in (a) and (b) are not equal.

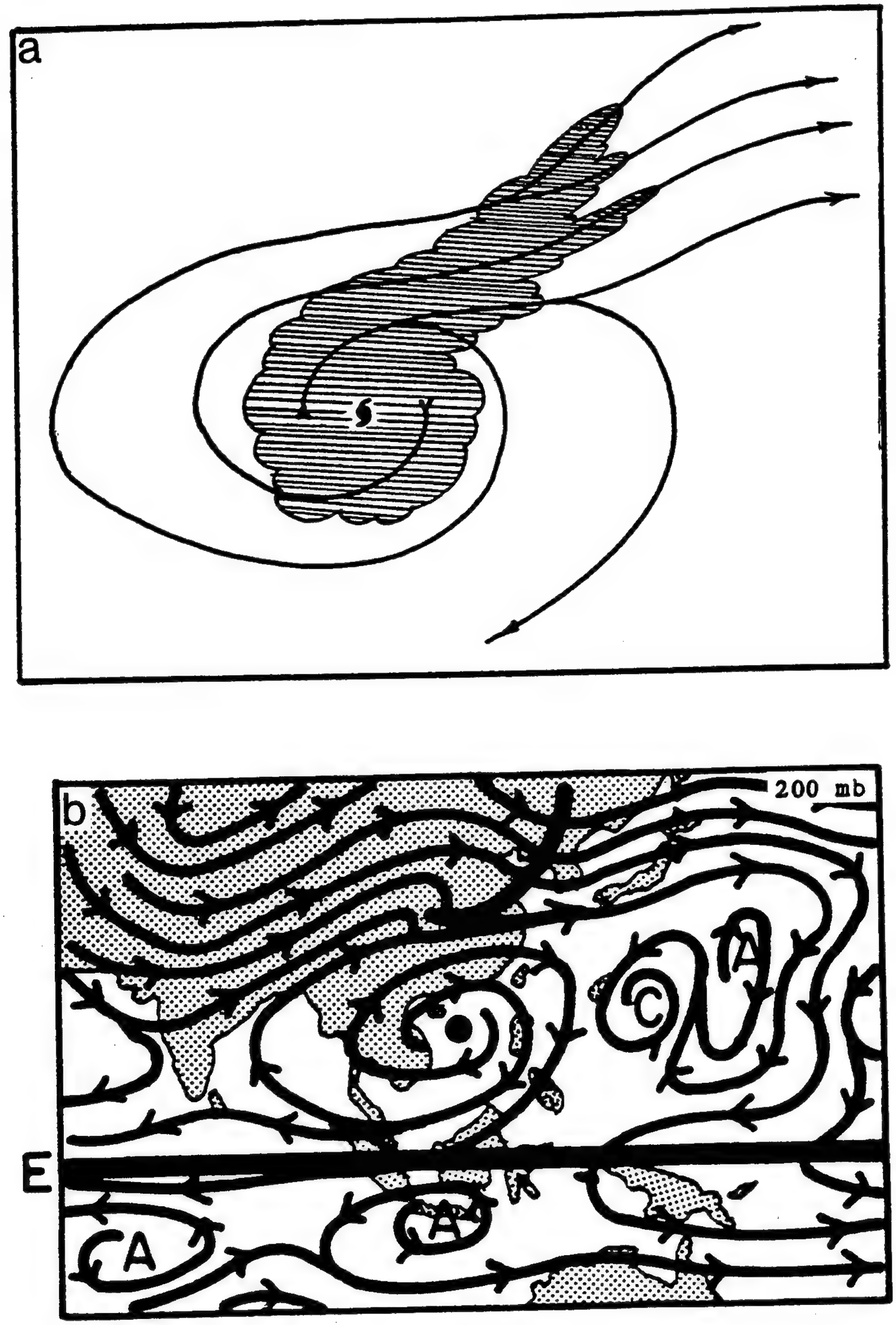

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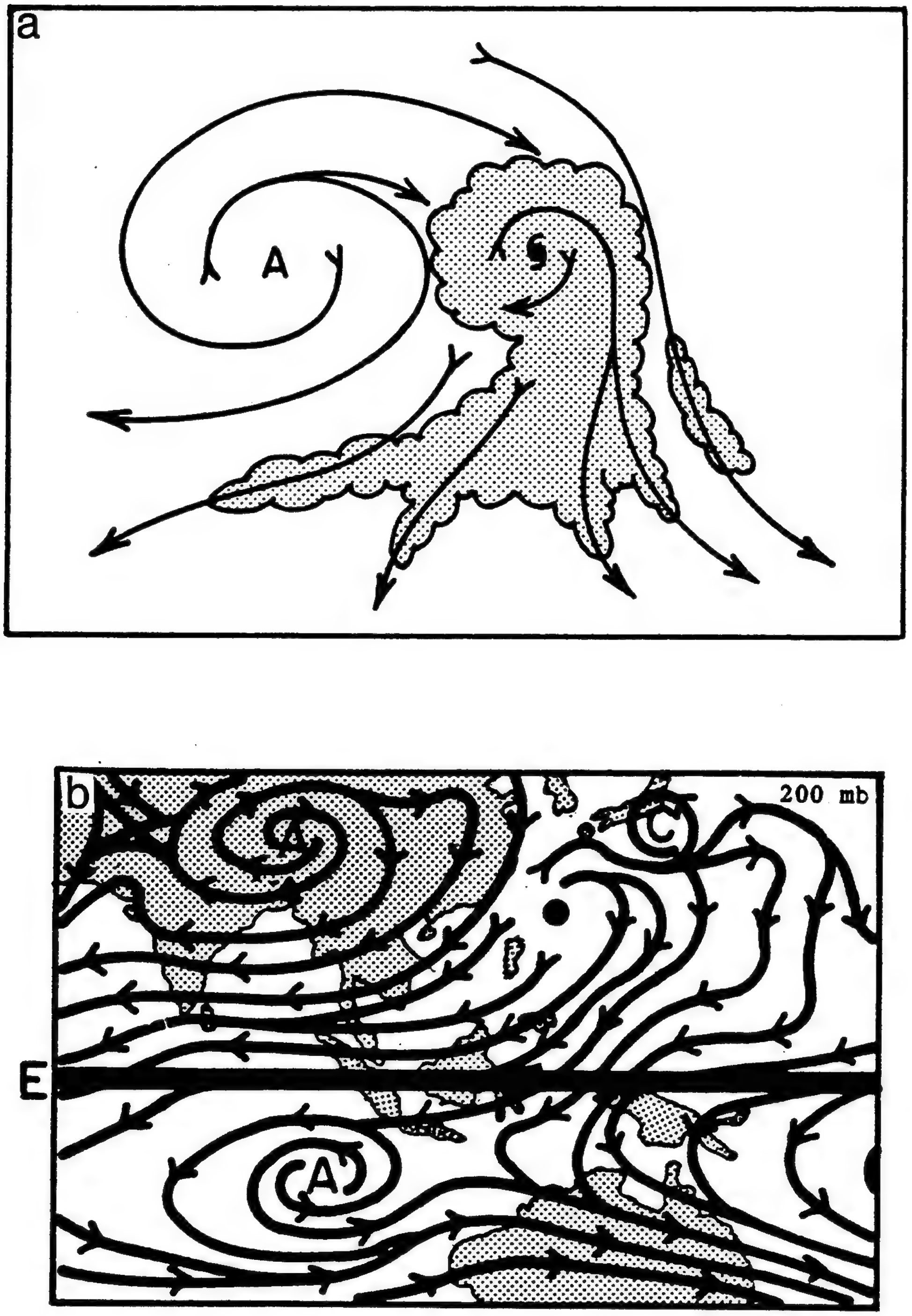
Fig. 6.3 Single-channel poleward outflow. (a) Idealized sketch of a single 200 mb poleward outflow channel with the 200 mb anticyclone center located directly over the cyclone center. (b) 200 mb streamlines for tropical storm Nancy on 18 September 1979 which had single-channel poleward outflow at the time. (Chen and Gray, 1985)



13 AUGUST 00Z

Fig. 6.4 Single-channel equatorward outflow. (a) Idealized sketch of a single equatorward outflow channel for a cyclone center to the east of the anticyclone center. (b) 200 mb streamlines for Typhoon Irving on 13 August 1979 that had single-channel equatorward outflow at the time. (Chen and Gray, 1985)

5.1.2 **Dual-channel Outflow**. Tropical cyclones with a dual-channel outflow pattern (Fig. 6.5) generally intensify at an average maximum rate of 35 kt/6 hr.

5.1.3 **No Outflow Channel**. Tropical cyclones with little outflow (Fig. 6.6) generally intensify at a very slow rate as they are unable to evacuate mass.

5.2 Tropical Upper Tropospheric Trough

A strong upper level (250-200 mb) cyclonic circulation to the north or northwest of a TC, namely the tropical upper tropospheric trough (TUTT or TUTT Cell), is a common occurrence during July and August in the northern Pacific. Sadler (1976) found that this type of upper-level circulation pattern is favorable for vigorous outflow to the north (Fig. 6.7a). In addition, this pattern generally occurs as the cyclone nears the western edge of the subtropical ridge where enhanced equatorward outflow is common (Fig. 6.7b). The combined effects of the northward and southward outflow often lead to rapid deepening.

5.3 Other Factors Affecting Intensity

There are a few other observable phenomena that can affect tropical cyclone intensity:

(1) Cumulus convection. Satellite cloud imagery can show whether convection is increasing or decreasing, and whether the TC cloud patterns become more or less organized. The convective activity implies the stage of TC development. Therefore, cumulus convection should be monitored continuously by the forecaster.

(2) SST. An SST of 26 °C is generally considered to be the minimum for TC formation. Anomalously high SST can cause more heat and moisture flux from the ocean to the atmosphere. This condition favors further development of the TC (Holliday and Thompson, 1979; Merrill, 1987). Table 6.7 indicates that rapid deepening is more likely once the SST is higher than 28.5°C. Climatological data show that the primary rapid-deepening area in the Pacific is the east Philippine Sea region (7-23 °N, 123-160 °E).

(3) Vertical wind shear. Weak vertical wind shear (e.g., less than about 15 kt and 45° between the surface and 300 mb for a TC located south of the subtropical ridge) aids TC intensification while strong vertical wind shear inhibits it.

(4) Low-level circulations. Low-level cyclonic circulations are favorable regions for TC intensification. The summer monsoon trough in the western North Pacific is an area where low level

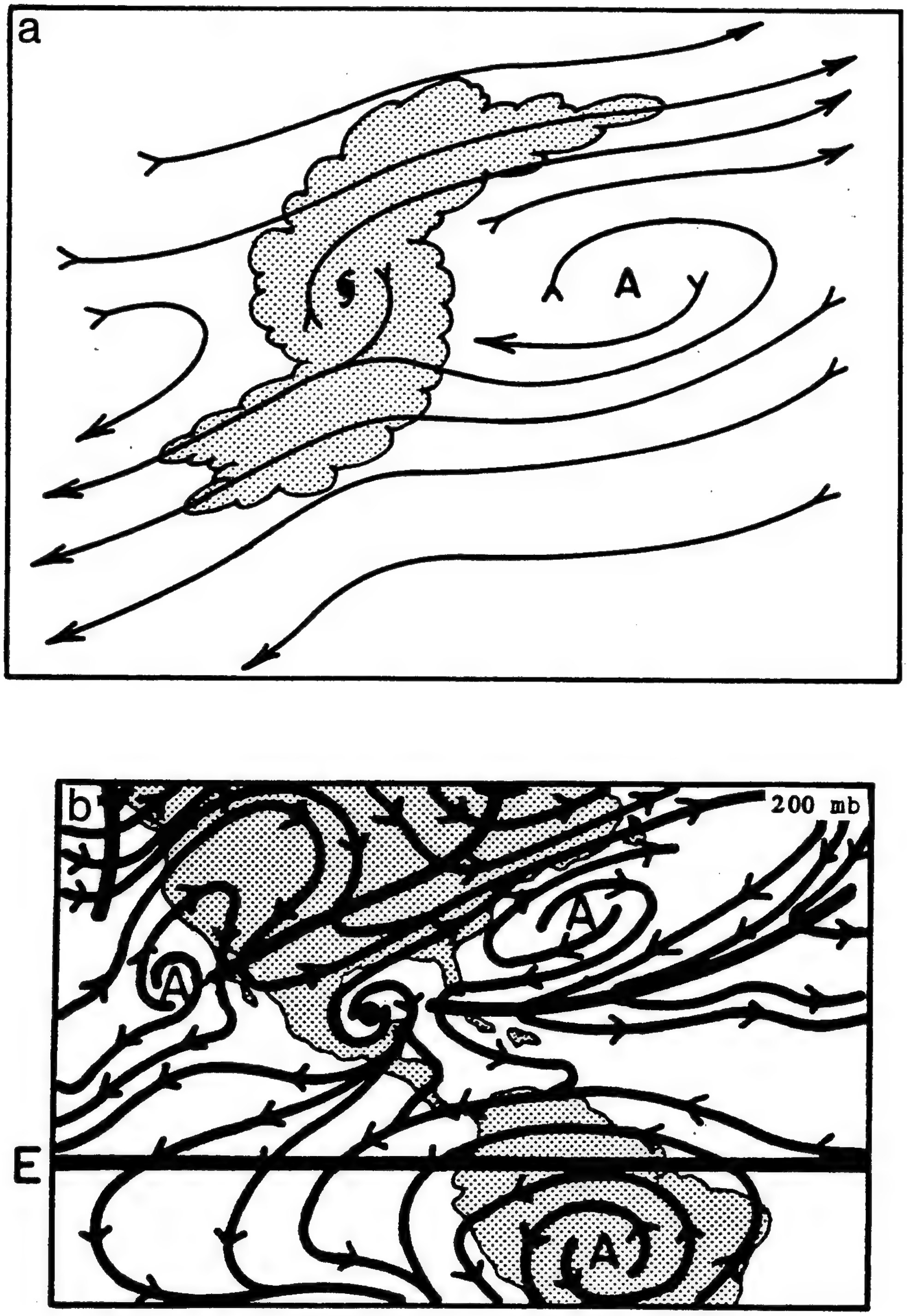


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Fig. 6.5 Dual-channel outflow. (a) Idealized sketch of a dual outflow channel with the cyclone center to the west of the anticyclone center. (b) 200 mb streamlines for future hurricane Henri on 16 September 1979 which had a dual-channel outflow at the time. (Chen and Gray, 1985)

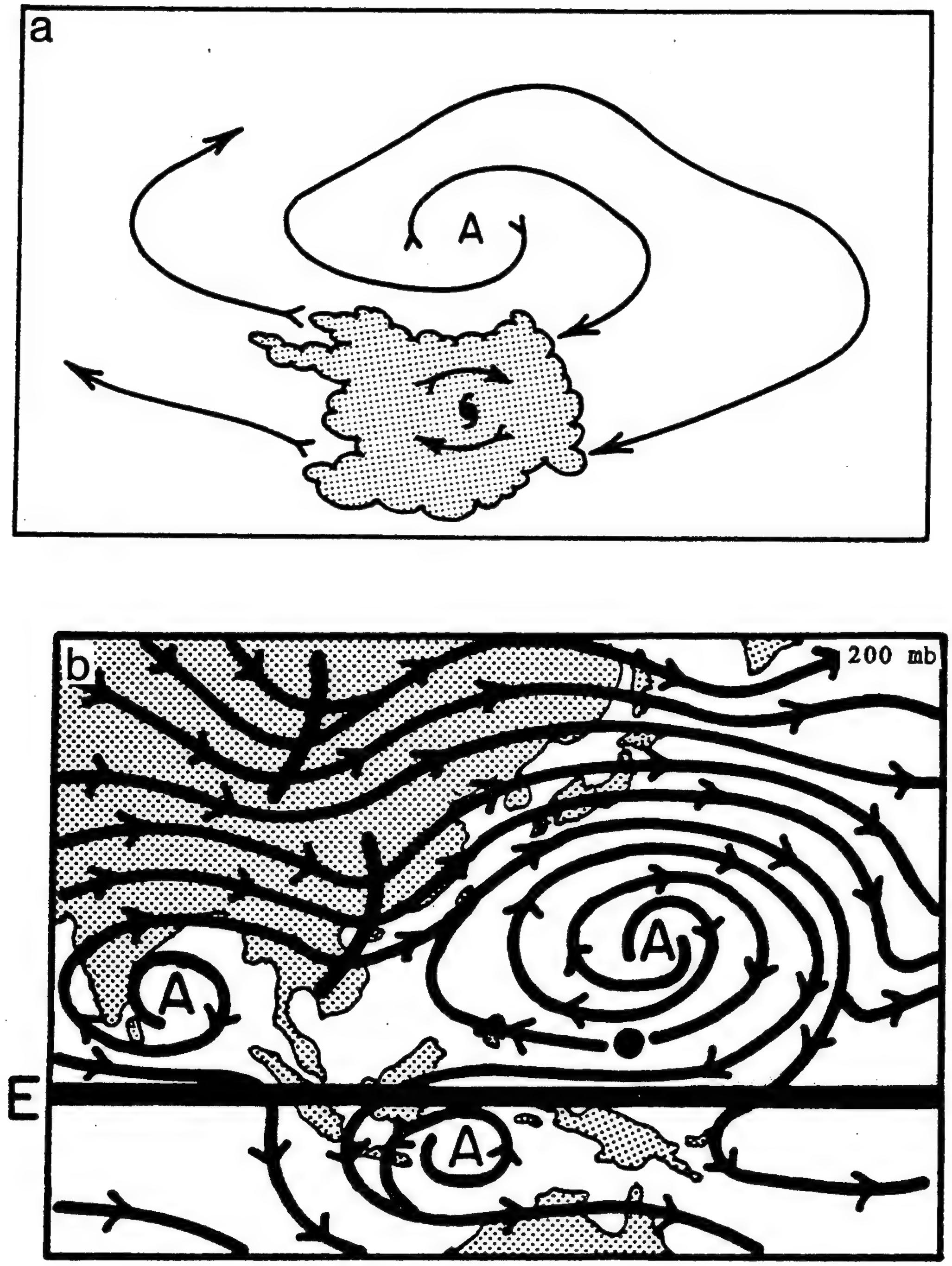

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Fig. 6.6 No outflow channel. (a) Idealized sketch with little outflow channel and with the cyclone center south of the anticyclone. (b) 200 mb streamlines for typhoon Vera on 3 November 1979 which had no outflow channel at the time. (Chen and Gray, 1985)

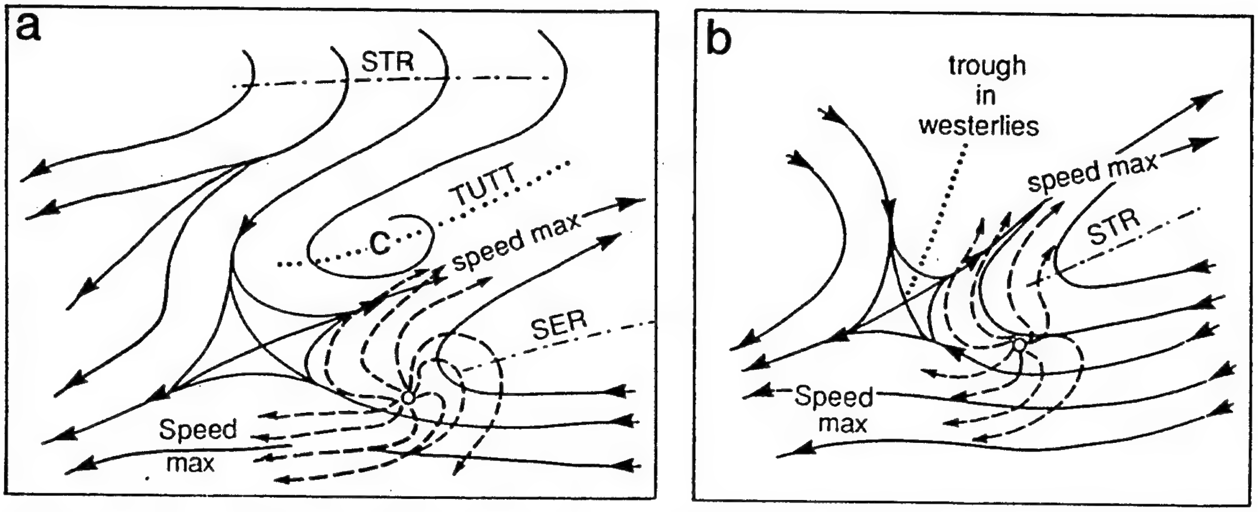

Figure 6.7. Two idealized upper-troposphere synoptic flow patterns that are associated with tropical cyclone intensification (Sadler, 1976). STR denotes the sub-tropical ridge; SER, the sub-equatorial ridge; TUTT, the tropical upper tropospheric trough.

cyclonic circulations are abundant. The Earth's rotation (Coriolis effect) also can also contribute to cyclonic circulation.

(5) Low-level convergence. Low-level convergence zones such as the Inter-Tropical Convergence Zone, are suitable areas for TC intensification.

(6) Land, coast, and mountain effects. These effects can be quite complex (Merrill, 1987). In general, a TC that moves over land decays. A TC decays much faster when it passes over mountainous regions, such as Taiwan or Luzon, than it does over flat land. Also, a TC often re-intensifies when it re-enters a marine area. Consult local rules of thumb for details on specific regions. For the Philippines, see Shoemaker (1991); for Taiwan, see Brand and Blelloch (1973).

(7) TC transformation. A TC that enters into the mid-latitudes either decays rapidly or transform into an extratropical cyclone. A decaying TC may still produce heavy rain, especially when it moves over mountainous areas. When a transformation from TC to extratropical cylone occurs, forecast responsibility is transferred from the tropical cyclone forecast center to another forecast office.

Table 6.7. Sea surface temperature considerations for tropical cyclone intensity forecasting.

Intensity characteristic	Observed SST (degree C)	Intensity forecast
Maximum intensity	26 - 29	860 mb central pressure
Minimum Intensity	20	Weak tropical cyclone
Intensity trend	> 28.5	Rapid developer

6. INTENSITY FORECASTS AND FORECAST PROCEDURES

Intensity forecast procedures vary between forecast agencies both in what parameters are emphasized and how the forecasts are developed. The following sections describes procedures used to forecast TC intensity.

6.1 JTWC Intensity Forecast

JTWC provides analyses and forecasts of maximum one-minute sustained surface wind speed (i.e., the maximum intensity), and the 35, 50, and 100 kt wind radii out to 72 hours when applicable.

According to Guard, et al. (1992), the procedure begins when the Dvorak technique (1984) (Appendix B) is used to determine the current intensity of a TC and as a first guess for the intensity forecast. The Typhoon Duty Officer (TDO) then adjusts the forecast after evaluating climatology and the synoptic situation.

An interactive conditional climatology scheme allows the TDO to define a situation similar to the system being forecast in terms of location, time of year, current intensity, and intensity trend. Synoptic influences such as the location of major troughs and ridges, and the position and intensity of the TUTT all play a large part in intensifying or weakening a TC.

JTWC incorporates an experimental intensity analysis and forecast checklist (Appendix D). Such criteria as upper-level outflow patterns, neutral points, sea surface temperatures, enhanced monsoonal or cross-equatorial flow, and vertical wind shear are evaluated for their tendency to enhance or inhibit normal development. These criteria are incorporated into the intensity forecast process through locally developed rules of thumb.

In addition to climatology and synoptic influences, the first guess is modified for interactions with land, with other tropical cyclones, and with extratropical features. Satellite cloud imageries help to assess the potential for development, rapid intensification, and time of peak intensity.

Climatological and statistical methods are also used to assess the potential for rapid intensification (Mundell, 1990). JTWC also has a statistical typhoon intensity forecast model, STIFOR, (Chu, 1994) that provides intensity forecasts out to 72 hours for 12-hour intervals. The STIFOR model an adaptation of the statistical hurricane intensity forecast (SHIFOR) model (Jarvinen and Neumann, 1979) which is used by NHC.

6.2 NHC Intensity Forecast

NHC provides intensity analysis and forecasts in terms of maximum one-minute sustained surface wind speed (i.e. the maximum intensity), the 34, 50, and 64 kt wind speed radii for 12, 24, and 36 hour forecasts, and the 50 kt wind speed radii for 48 and 72 hour forecasts.

According to Sheets (1990), intensity forecasts are developed at NHC using empirical synoptic pattern recognition, satellite and aircraft data, and two statistical models, SHIFOR (Jarvinen and Neumann, 1979) and SHIPS (DeMaria and Kaplan, 1994), the latter still being classified as an experimental model.

All of the empirical techniques are centered on a qualitative assessment of changes in the environment and environmental flow patterns affecting the TC. SHIFOR is a blend of climatology and statistics with the heaviest weight on climatology near 72 hours. The NHC forecasters use all of these techniques to build the intensity forecast, which is mutually dependent on the motion forecast. This information is provided to the field forecast offices and field users who may amplify the information based on local conditions.

6.3 US DOD Single Station Intensity Forecast Procedures

One of the most important tasks assigned to forecasters is providing recommendations to area and task force commanders who set conditions of readiness. In order to generate the recommendations, forecasters must assimilate a tremendous amount of data in a short period of time. The following four-step procedure is recommended when making TC intensity forecasts.

Step 1: Pre-deployment. Forecasters are advised to understand the mission, and to review the Hurricane Havens and Typhoon Havens Handbooks (U.S. Navy 1976, 1982), and the applicable Fleet Operation Orders that govern the ship's operations on deployment.

The handbooks indicate which ports are considered storm havens and which are not, and the maximum wind speeds that constitute sortie criteria. This information should be provided to operations officers and commanding officers during the predeployment briefings and prior to any expected port visits.

Step 2: Analysis. When a TC develops or moves into the forecast area, plot the warning and analyze the current synoptic environment to determine key synoptic features affecting the intensification/dissipation trend. This analysis should center on verification of the intensification and dissipation rate issued by the forecast center.

One suggested approach for analyzing the current synoptic environment is to plot 48 hours worth of past storm positions on the corresponding numerical analysis (e.g., NOGAPS 250 mb analysis). Then, locate synoptic features within 30 degrees longitude and latitude of the TC by paging through the analyses. Try to identify the synoptic features that affect TC intensity. The synoptic features that affected TC intensity in the recent past may also affect it in the near future.

Next, determine intensity trends using intensity observations available over the past 24 to 48 hours. Each intensity observation should be compared with the previous observations from the same site and same type of observation platform. This is necessary because each fixing agency has its own unique method to determine TC intensity which depends on available equipment, data, and operating procedures.

Step 3: Forecast Verification. Verify the TC intensity forecast in the official forecast for accuracy and significant departures from previous forecasts. First, plot the official intensity forecasts on the verifying prognostic charts from the numerical model (e.g., the NOGAPS 250 mb 48 hour prognostic charts). Next, note the location with respect to major synoptic features identified during the previous step. An initial assessment of forecast confidence can now be made. Table 6.8 shows some examples of confidence value assignments.

If a low confidence scenario is identified during the intensity forecast verification step, try to understand the reasons for the official forecast trend. A review of the synoptic and prognostic discussions issued by forecast centers should shed some light on the situation. Many times the forecast center is moving from one primary forecast scenario to another (e.g., a maximum intensity of typhoon to a super typhoon or vice versa). In this case, the prognostic discussions should describe the alternate scenario.

Step 4: Forecast Recommendations. Brief the forecast intensity, but be sure that the customers also understand the intensity forecast errors. The intensity forecast has a mean absolute error of approximately 11 kt at 24 hours, 18 kt at 48 hours, and 24 kt at 72 hours (see Table 6.3). However, 72-hr errors of 50 kt or greater do occur over a 72-hour period several times each year.

In connection with this, consider a situation where ships must sortie from Guam when the winds are expected to exceed 50 kt sustained over the island. If a TC, forecast to be 45 kt as it crosses Guam, actually intensifies to 100 kt, ships remaining in port may be damaged. When users are briefed the intensity forecast including the errors inherent in the forecast, they can make informed decisions, such as whether or not to sortie the ships in the case described above.

Table 6.8. Examples of intensity forecast confidence values.

Current TC Outflow Pattern	Environment Is Able To Sustain ...	Official Forecast Trend	Confidence Value
Single Equatorward	Single Equatorward	Normal Development	High
Single Poleward	Single Poleward	Normal Development	High
No Outflow	No Outflow	Slow Development	High
Single Equatorward	No Outflow	Normal Development or Rapid Development	Low
Single Poleward	No Outflow	Normal Development or Rapid Development	Low
No Outflow	No Outflow	Normal Development or Rapid Development	Low
Dual Outflow	No Outflow	Normal Development or Rapid Development	Low
Single Equatorward	Dual Outflow	Normal or Slow Development	Low
Single Poleward	Dual Outflow	Normal or Slow Development	Low
No Outflow	Dual Outflow	Normal or Slow Development	Low
Dual Outflow	Dual Outflow	Normal or Slow Development	Low
Dual Outflow	Dual Outflow	Rapid Development	High

For the forecaster in harm's way, the short term loss of communications and other equipment failures frequently occur. However, this does not preclude the requirement to make forecast recommendations. The forecaster who follows the procedures above will be able to make reasonable forecast recommendations to the on-scene commanders.

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APPENDIX A

MEAN WIND SPEED CONVERSION TABLES

Tables A-1 and A-2 are provided so that the forecaster can compare intensity forecasts issued by various warning agencies.

Table A-1. Conversion from 10-minute mean wind speeds to 1-minute mean wind speeds in kt (ONE-MINUTE MEAN = 1.14 * TEN-MINUTE MEAN).

10-MINUTE MEAN SPEED	1-MINUTE MEAN SPEED	10-MINUTE MEAN SPEED	1-MINUTE MEAN SPEED
30	34	85	97
35	40	90	103
40	46	95	108
45	51	100	114
50	57	105	120
55	63	110	125
60	68	115	131
65	74	120	137
70	80	125	143
75	86	130	148
80	91	135	154

Table A-2. Conversion from 1-minute mean winds to 10-minute mean wind speeds in kt (TEN-MINUTE MEAN = 0.88 * ONE-MINUTE MEAN).

1-MINUTE MEAN SPEED	10-MINUTE MEAN SPEED	1-MINUTE MEAN SPEED	10-MINUTE MEAN SPEED
30	26	85	75
35	31	90	79
40	35	95	84
45	40	100	88
50	44	105	92
55	48	110	97
60	53	115	101
65	57	120	106
70	62	125	110
75	66	130	114
80	70	135	119

APPENDIX B

DESCRIPTION OF THE DVORAK TECHNIQUE

The objective of this section is to provide an overview of the Dvorak technique (Dvorak, 1973, 1984). This technique supplies the bulk of tropical cyclone fixes for the Pacific and Indian Oceans. Although mean absolute errors inherent in intensities obtained through the Dvorak technique are large (approximately 15 mb), these fixes are treated as ground truth in many tropical cyclone intensity forecast verification studies. The following provides an outline of the steps required to develop an intensity estimate (CI) and forecast when using the Dvorak technique.

1. **How has the Disturbance Changed Since the Previous Observations?** The current satellite imagery is compared with the picture from the previous observation (approximately 24 hours long term and 6 hours short term). Has it developed, remained the same, or weakened?

2. **Current T-Number is Assigned.** The central cloud features and banding features are compared using various satellite enhancement curves and templates. A current T-number is assigned based on these comparisons. A T-number which may range from T1 to T8 is defined as a description of a TC in terms of cloud characteristics visible in satellite imagery. The current intensity is then computed using the T-number and a few rules for re-developing or weakening storms. The CI number is considered the best estimate of the current maximum winds and sea-level pressure of the TC. Table B-1 lists the CI numbers and their approximate intensity.

3. **Indications of Ongoing Change.** A disturbance will normally exhibit indications of intensification or weakening in the satellite imagery as it develops or weakens. A Plus or Minus sign may be added to the code when the dominant signs of ongoing change conflict with the trend indicated in the observation.

4. **24 Hour Forecast Intensity.** The normal forecast intensity change using the Dvorak model is one T-number increase or decrease during a 24 hour period. A plus or minus sign will be added to the code to indicate a slower or faster trend.

Table B-1. CI numbers versus maximum 1-minute sustained surface wind speeds.

Current Intensity (CI) Number	Maximum Sustained Surface Wind Speed (kt)
1.5	25
2.0	30
2.5	35
3.0	40
3.5	50
4.0	60
4.5	72
5.0	85
5.5	97
6.0	110
6.5	122
7.0	135
7.5	150
8.0	170

APPENDIX C

PHYSICAL PROCESSES ASSOCIATED WITH TROPICAL CYCLONE INTENSITY CHANGES

Table C-1 provides a summary of some physical processes that contribute to the intensification or decay of tropical cyclones.

Table C-1. Physical processes contributing to a tropical cyclone's intensification or decay. The positive and negative contributions are denoted by + and - signs, respectively.

Physical Processes and Flow Regimes		Intensification	Decay
1. Lower-troposphere cyclonic vorticity, monsoon trough, and wave disturbance		+	-
2. Upper-troposphere disturbances, such as midlatitude wave, TUTT		+	-
3. Strong vertical wind shear		-	+
4. Warm sea surface temperature (SST), deep oceanic well-mixed layer, and upward moisture and heat fluxes from the sea surface		+	-
5. Heavy precipitation (both convective and stratiform)		+	-
6. Fast tropical cyclone motion speed (faster than 10 m/s)		-	+
7. Topographic effects	Island with mountain range	induced lows and corner vortices, vortex re-establish after cyclone center moves across mountain range	momentum dissipation, weakening of heat and moisture supply in the boundary layer
	Coastal	confluent line due to differential surface friction	momentum dissipation, weakening of heat and moisture supply
8. Recurvature	Before	+	-
	During	?	?
	After	?	?

Table C-1. Continued

Physical Processes and Flow Regimes	Intensification	Decay
9. Tropical cyclone imbedded in a low-level col region	with upper-troposphere divergence	without divergence
10. Tropical cyclone and extra-tropical cyclone	merging and transformation	not merging
11. Tropospheric large-scale eddy fluxes of cyclonic angular momentum	inward (radial)	weakly inward or outward
12. Tropospheric large-scale eddy fluxes of heat	inward	weakly inward or outward
13. Lower- and middle-troposphere large-scale eddy fluxes of moisture	inward	weakly inward or outward
14. Stratospheric quasi-biennial and semiannual oscillations	+	?
15. Conditional instabilities of the first kind (CIFK) for deep cumulus when the air is moist enough	+	deep cumulus may dissipate
16. Conditional instabilities of the second kind (CISK) for the cooperation between cumulus ensemble and lower- troposphere cyclone-scale vortex	+	-
17. Upper-troposphere organized outflow or outflow cloud patterns	+	-
18. Middle- or upper-troposphere cold air advection	+	-
19. Degree of organization of cumulus cloud and spiral cloud bands	high	low

APPENDIX D

JTWC EXPERIMENTAL TROPICAL CYCLONE INTENSITY ANALYSIS AND FORECAST CHECKLIST

JTWC has developed an experimental checklist for intensity analysis and forecast in the Northern Hemisphere (Table D-1). The first part is for intensity analysis and consists of four elements. The elements are:

1. Dvorak classification for current intensity,

2. Synoptic influences and upper troposphere outflow patterns,

3. Sea surface temperature influences, and

4. Dvorak trend estimation and cloudiness.

The second part is an intensity forecast that assesses future tropical motion, mid-latitude wave disturbances, tropical upper troposphere troughs, monsoonal and cross equatorial flow patterns, current satellite cloud imagery and outflow patterns.

To complete the checklist, determine a yes/no answer for each of the criteria listed. Sum up all the points assigned for yes answers. Finally, look up an intensity assessment using the total score. Some terms used in the checklist are explained after the checklist.

Table D-1. NORTHERN HEMISPHERE INTENSITY FORECAST CHECKLIST

INTRODUCTION: This checklist consists of two parts: intensity analysis and forecast. The forecast part, part 2, contains 24-, 48- and 72- hour forecasts. The checklist is designed to coincide with the four intensity determinations needed to assess the intensification trends over 72 hours.

Part 1. TROPICAL CYCLONE INTENSITY ANALYSIS CHECKLIST: The following criteria should be evaluated using the information from the analyses that correspond to the initial position of the warning.

CRITERIA	POINTS
1. DVORAK CLASSIFICATIONS	
-Current Dvorak Intensity 3.0 - 4.0	2
-Current Dvorak Intensity 4.0 - 5.0	0
-Current Dvorak Intensity 5.0 - 6.0	-2
2. SYNOPTIC INFLUENCES/OUTFLOW PATTERNS	
-200 mb Anticyclonic Outflow Present in synoptic data over cyclone.	1
-200 mb Cyclonic Outflow Present in synoptic data over cyclone.	2
-No Organized 200 mb Outflow Present Over Cyclone	-1
-No Outflow Channels Present in Cloud Pattern	-2
-Single Poleward Outflow Channel Present In Cloud Pattern	1
-Single Equatorward Outflow Channel Present In Cloud Pattern.	2
-Dual Synoptic Scale Anticyclones Present In Both Hemispheres Adjacent To The Cyclone With A Single Equatorward Outflow Channel Present In The Cloud Pattern.	3
-Dual Outflow Channels Present In The Cloud Pattern.	4
-TUTT Cell Located Northwest Of Cyclone Within 10-12 Degrees of Storm Center	5
3. SEA SURFACE TEMPERATURE INFLUENCES	
-Cyclone Moving Over Warmer SSTs (>26 C)	1
-Cyclone Stalled Over Warm SSTs Longer Than 18 Hours (upwelling)	-2
-Moving Over Cold SSTs (<24 C)	-3
4. DVORAK TRENDS	
-Current Development Trend is W1.5 - W1.0/24 hrs	-4
-Current Development Trend is W0.5 - S0.0/24 hrs	-2
-Current Development Trend is D0.5 - D1.0/24 hrs	0
-Current Development Trend is D1.5 or >/24 hrs	2
-CDO Developing Over Cyclone	2
-CCC Developing Over Cyclone	-2
TOTAL SCORE	______

ASSESSMENT

8 or >	: Fast Developer, Dvorak Forecast Intensity 1.5 or greater.
4 to 7	: Standard Developer, DVORAK Forecast Intensity 1.0.
-5 to 3	: Slow/Steady, Developer DVORAK Forecast Intensity 0.5 or less.
-6 to -17	: Weakening.

Part 2. TROPICAL CYCLONE INTENSITY FORECAST CHECKLIST FOR 24-, 48- and 72- HOUR FORECAST PERIODS.

CRITERIA	POINTS		
SYNOPTIC INFLUENCES/OUTFLOW PATTERNS	24 hr	48 hr	72 hr
-Is The Cyclone Moving Into The Southeast Quadrant or Southern Side Of The Upper-Level Anticyclone?	-2	-2	-2
-Is The Cyclone Moving Into The Southwest Quadrant Of The Upper-Level Anticyclone?	2	2	2
-Is A Mid-latitude Long-wave Trough Moving To Within 4 to 6 Degrees To The West Of The Cyclone Or Is A TUTT Cell Forecast To Be 10-12 Degrees Latitude NNW Of Storm?	2	2	2
-Is A Mid-Latitude Shortwave Trough Expected To Pass Within 15 Degrees Latitude Of The Cyclone?	1	1	1
-Is The Cyclone Moving Into An Area Where The Equatorward Outflow Channel Will Be Enhanced By An Upper-Level Anticyclone In The Opposite Hemisphere?	1	1	1
-Is The Cyclone Moving Into An Area Of Enhanced Monsoonal/Cross Equatorial Flow?	1	1	1
-Is The Cyclone Moving Over Warmer SSTs?	1	1	1
-Is The Cyclone Moving Over Colder SSTs?	-2	-2	-2
-Is The Cyclone Moving Into An Area Of Stronger Vertical Wind Shear?	-3	-3	-3
-Is The Cyclone Moving Into The Neutral Point Between Branches Of The Subtropical Ridge?	3	3	3
TOTAL SCORE	______	______	______

Note: The tropical cyclone forecast positions should be superimposed on the current NOGAPS prognostic series to determine the above criteria.

ASSESSMENT

8 or > : Fast Developer, Dvorak Forecast Intensity 1.5 or greater.
5 to 7 : Standard Developer, Dvorak Forecast Intensity 1.0.
-2 to 4 : Slow/Steady Developer, Dvorak Forecast Intensity 0.5 or less.
-3 to < : Weakening.

Checklist Terminology

CCC developing: Central cold cover (CCC) occurs when the central dense overcast (CDO) becomes glaciated across the top, wiping out the thermal gradient normally observed with the CDO of an intensifying TC. The CCC indicates arrested development for a period of 12-24 hours. The Dvorak trend is S0.0 as opposed to the D1.0 for normal development. When a CCC develops, the visual imagery may indicate a circular exhaust cloud where a single cumulonimbus penetrates the CCC or CDO and produces a canopy of concentric gravity waves. This occurs in the T3.5 to 4.0 range.

CDO developing: Central dense overcast (CDO) occurs when tropical cyclone wind speeds reach the 45-55 kt range (T number is in the range from 3.0 to 3.5), and is the precursor to the formation of an eye. The alternative to eye formation without a CDO is through the development of a banding type eye where the primary convective band curves around the center until it forms a closed convective ring. This also occurs at about T 3.5. The CDO frequently contains penetrative cumulonimbus that can be used to help locate the center. The CDO also has a circular temperature gradient with the coldest temperature near the center. As the CDO evolves, a warm spot appears. This is the first hint that subsidence is beginning to clear the cloud from the upper portions of the eye.

cross equatorial flow: For the northern hemisphere, flow originates south of the equator and moves north across the equator. In this case, cross equatorial flow can contribute to convergence in the northern hemisphere.

neutral point: same as col or saddle point. A neutral point on a surface chart is the location of a relative low pressure between two highs and the location of a relative high pressure between two lows.